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Decay of Agulhas rings due to cross-frontal secondary circulations

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Abstract. A series of idealized numerical experiments is presented to study the evolution of an Agulhas ring. The modeled ring is a circular symmetric idealization of ring Astrid, as measured by a cruise in March 2000. In particular, the hypothesis is tested that mixing is mainly due to cross-frontal secondary circulations. Both the role of beta-decay and shear instabilities in setting-up cross-frontal mixing is studied. The largest mixing of ring water with its surroundings occurs in the first months after shedding when the heat loss is maximal. Therefore, it is tested whether buoyancy forcing is able to enhance cross-frontal circulations. It is concluded that for realistic initial conditions the observed decay can be accounted for by adiabatic decay associated with cross-frontal circulations. The adiabatic decay appears to be a nonlinear function of the ring strength, possibly enhanced by the instability of the ring. The relative decay for weaker, stable rings is more than twice as weak. For a wide parameter range all modeled rings are unstable for a mode-2 perturbation and split. Observations suggest that most rings do not split and are not as unstable as suggested by the model. What causes this mismatch and how it affects the decay rate is still unclear. Realistic cooling is observed to slightly retard the split and marginally stabilize the ring. The decay rate is enhanced with typically 30%. For weaker rings the impact of cooling becomes less.

Introduction

In Autumn 1999, the Netherlands consorted observational and modeling program MARE (Mixing of Agulhas rings Experiment) was started (*Lutjeharms et al.*, 2000). The main goal is to estimate the proportion of Agulhas leakage that contributes to the upper branch of the thermohaline circulation and identify the dominant mixing processes that determine that proportion. The experiment is motivated by the observation that the sea surface height anomaly of Agulhas rings most rapidly decays just after shedding (*Schouten et al.*, 2000). Figure 1 shows the mean sea surface height (SSH) anomaly of 11 Agulhas rings as a function of age. During the first 5 months the decay is fast: 5 cm per month. After 10 months the rings decay very slowly: 0.5 cm per month. As a result, in the early phase when Agulhas rings cross the Benguela Current, the associated density anomaly for a large part is mixed away into the surroundings. The Benguela Current is thought to be the main agent for the North Atlantic Deep Water (NADW) return flow in that region (*De Ruijter et al.*, 1999). So, the mixing process(es) associated with the fast decay regime in the early phase of Agulhas rings mainly determines the proportion of Agulhas leakage that contributes to the NADW return flow.

To determine the mixing associated with the fast decay regime from measurements only, requires an observational database that contains an amount of detail which is not feasible with present day measurement techniques. Therefore, MARE consists of a hierarchy of modeling efforts to support the observational program. Here, we report a series of model simulations initialized with a circular symmetric idealization of ring Astrid, as measured by the first MARE cruise. In particular, we test the hypothesis that mixing is mainly due to cross-frontal secondary circulations. That is, the associated mixing is predominantly adiabatic (stirring). The stirring itself may have various dynamical origins which can be adiabatic (e.g., β-decay, baroclinic instability), or diabatic (e.g., cooling, double diffusion).

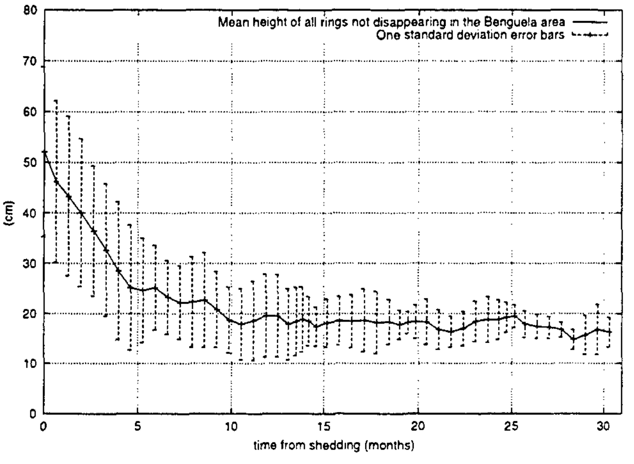

Figure 1. Mean SSH anomaly (and bars of 1 standard deviation) of Agulhas rings plotted against their age from *Schouten et al.* (2000).

Both observations and modeling efforts have shown that secondary circulations may arise due to internal instabilities (e.g., *Pollard and Regier*, 1992; *Spall*, 1995). In the case of convective chimneys, cooling sets the stage for baroclinic instability. Stirring is associated with baroclinic instability-driven intrusions (*Legg and McWilliams*, 2000). As the largest mixing of ring Water with its surroundings coincides with maximum heat loss, we test whether cooling is able to maintain/enhance cross-frontal stirring and whether this is the main driving agent for the decay of Agulhas rings.

Experimental setup

The simulations we analyze have been performed with MICOM 2.7, which is an extended version of the ocean general circulation model described by *Bleck and Smith* (1990). The horizontal resolution is 0.05° in longitude and latitude and there are 12 layers in the vertical. Computations were carried out on a 201 x 201 periodic domain with a flat bottom at 4000 m depth. The model was initialized with a circular symmetric idealization of ring Astrid. First, for 12 selected depth intervals, the average σ_0 outside the ring was calculated from the measurements. These σ_0 values were assigned to the isopycnic layers. Then, the σ_0 value at 50 m depth outside the ring (the bottom of layer 1) was estimated, and the depth of this σ_0 level was assessed as a function of the radial distance from the ring center. The curve, so obtained, was fitted to a linear profile (solid body rotation) inside the ring, and an $\exp(-r)^2$ profile outside the ring. The bounding edge between inside and outside was defined by the velocity maximum of the ring.

The same profile was used for all layer depths, implying an equivalent barotropic structure. The amplitude as a function of layer number was obtained by evaluating the σ_0 values at the undisturbed layer depths outside the ring, and then calculating the depth of this σ_0 level at the ring center. The temperature profile was obtained in an analogous way and the salinity profile was calculated from the associated temperature and σ_0 values. The barotropic pressure gradient was assumed to compensate the baroclinic pressure gradient in the deepest layer. The initial velocity field was obtained by demanding cyclogeostrophic balance.

Due to the periodic boundary conditions there is a discontinuity in f and potential vorticity at the north/south boundary. This does not affect the ring structure, which is initialized in the middle of the domain, but it affects the barotropic waves that radiate away from the ring. As the barotropic waves re-enter the domain due to the periodic boundary conditions, they interact with the ring and this interaction is influenced by the north/south potential vorticity discontinuity. The impact on the ring of this interaction with the barotropic wave field is assumed to be small and not to affect the evolution characteristics of the ring.

In a few simulations the model was forced with uniform cooling to 16°C, with an average wind field of 7 m/s. This value was estimated from the wintertime SST for the same ring, as measured during the second MARE cruise. Initially, temperature in the surface layer was 18.43°C outside the ring, 20.53°C at the ring center. A uniform cooling to 16.0 °C implies entraining layer 2 and part of layer 3 with initial values of 12.82°C outside the ring and 14.58°C at the ring center. Layer 3 is between 100 and 200 m depth outside the ring, between 320 and 520 m depth at the ring center.

Results

Stability characteristics

The stability of the modeled ring appeared to be highly sensitive to details of the initial profile, that is, both the horizontal shape and vertical profile. Horizontal shapes that feature vorticity maxima within the ring (e.g., an $\exp(-r)^2$ profile) generally induce quickly developing instabilities. Also, the vertical profile matters. Two different profiles with the same two-layer integrated properties (σ_0 and interface displacement) may show completely different stability behavior. In this case, the amplitude of the barotropic and first baroclinic mode is the same, but the amplitude of the higher baroclinic modes differ. Apparently, the amplitude of the higher baroclinic modes have a strong impact on

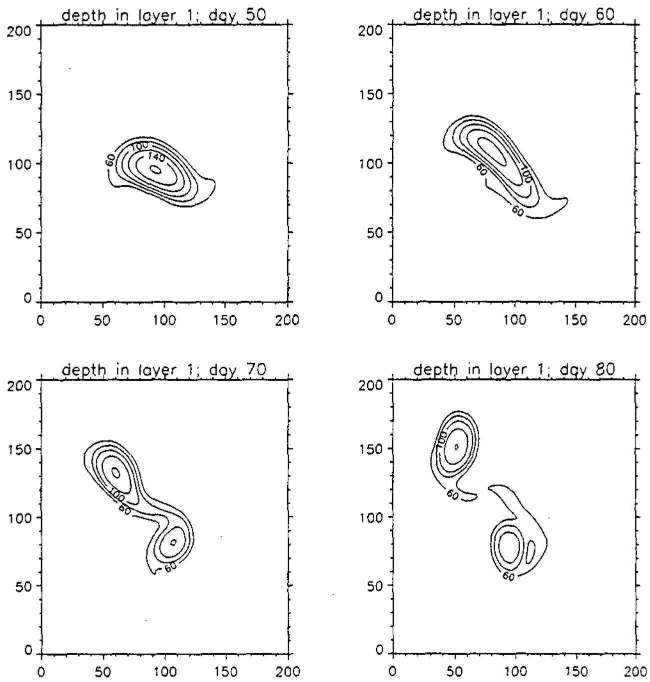

Figure 2. Thickness of the upper layer at days 50, 60, 70 and 80 with alpha=1. Contour interval is 20 m.

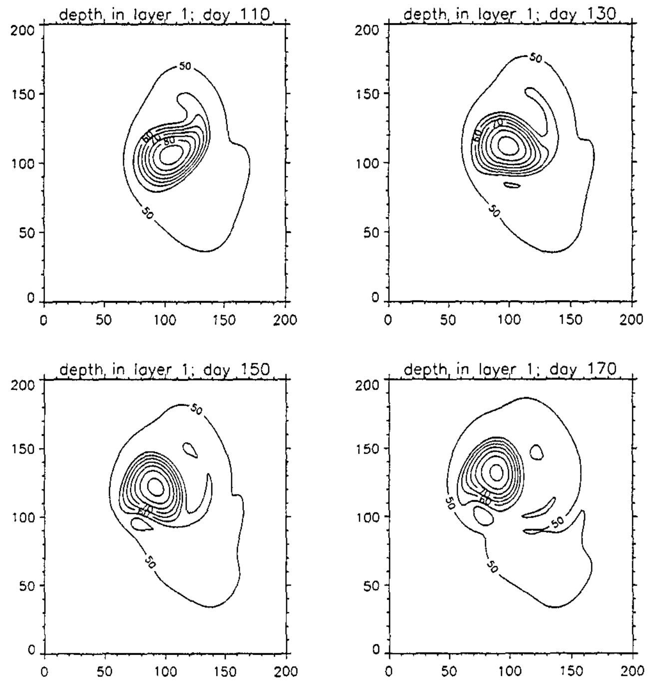

Figure 3. Thickness of the upper layer at days 110, 130, 150 and 170 with alpha=0.33. Contour interval is 5 m.

the stability characteristics of the ring, and as a result, the two-layer stability results of *Dewar et al.* (1999) do not simply extrapolate to a multilayer setting.

All runs we discuss here use nearly the same parameter setting, which is derived from ring Astrid. The only parameter we vary is the overall strength. In all runs both the barotropic pressure gradient and interface displacements are multiplied with one and the same factor α. With $\alpha = 1$ the ring mimics ring Astrid. This ring is unstable for a mode-2 perturbation and the ring splits after 80 days. Figure 2 shows the evolution of upper layer thickness between day 50 and 80. At day 50 the ring has become ellipsoidal. At day 60 it is even more elongated. At day 70 a neck is forming in the middle, and at day 80 the ring is split into a slightly weaker and a stronger half.

The ring remains unstable while decreasing α to 0.5. When we decrease α further to 0.44 the ring becomes stable, that is, the ring sheds off satellites that become increasingly smaller and weaker relative to the parent ring with decreasing α. Figure 3 shows the evolution of upper layer thickness between day 110 and 170 for $\alpha = 0.33$. The ring becomes much less ellipsoidal. It develops streamers from which at intervals small satellites are cut off.

The strong tendency of ring Astrid to split is remarkable. *Schouten et al.* (2000) tracked 20 Agulhas rings using TOPEX/Poseidon satellite altimetry. Of those 20, 6 split, and 14 remained stable. As the strength of Astrid appears not to be a critical parameter, either the density stratification, or, the vertical profile of the rings should enhance the stability. In our calculations a change in stratification did not have a very strong impact, while a change in vertical profile in general made the ring more unstable. An alternative explanation could be that for the observed rings (nonlinear) interaction with the background flow, or, with other rings and cyclones could prevent splitting. Also, the bathymetry could stabilize the rings.

Decay

When calculating the SSH anomaly as a function of time for the unforced runs with $\alpha = 1$, it appears that the decay rate is consistent with the fast decay regime shown in Fig. 1. The cross-frontal mass exchange is associated with a single-cell secondary circulation that implies upwelling at the back of the ring and downwelling at the face of the ring (Fig. 4a). Here, back and face are defined along the β-induced movement. On the basis of potential vorticity considerations we would expect f-plane subduction to occur at the edge of the ring and upwelling in the middle when some sort of confluence is present near the ring edge (e.g., *Pollard and Regier*, 1992; *Spall*, 1995). This confluence can be provided for by the developing baroclinic instability. Apparently, the instability process develops slowly for Agulhas rings, so

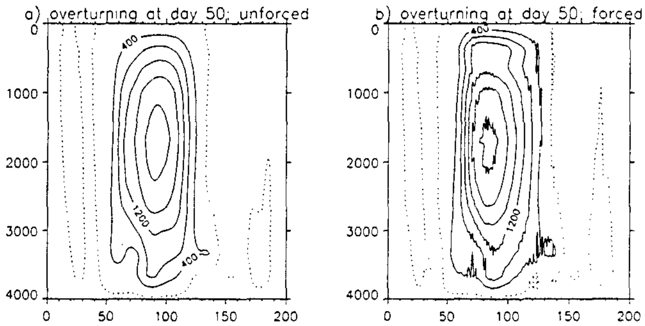

Figure 4. Meridional overturning at day 11 with alpha=1. Units are in milliSverdrups. a) left panel unforced run; b) right panel run with cooling.

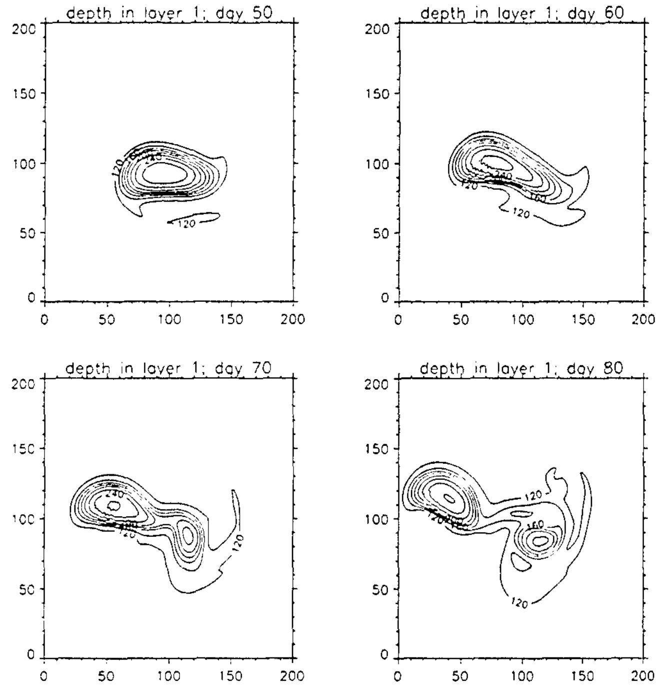

Figure 5. Thickness of the upper layer at days 50, 60, 70 and 80 with alpha=1., and cooling turned on.

that the associated confluence is too weak to overcome the β-induced movement. The resulting single-cell overturning slightly extends across the ring boundaries and is associated with adiabatic stirring of the ring's density anomaly across its boundaries. When the ring is stable the associated adiabatic decay is (relatively) more than twice as slow, too weak to account for the observed fast decay regime. It is disturbing that the observed rings seem less unstable but still show a decay rate that is only found for modeled rings that are unstable.

When we allow for cooling, convection initially modifies the β-induced overturning cell. Figure 4b shows the meridional overturning at the same stage (day 50) as Fig. 4a, but now with cooling turned on. The convection-induced modification on the overturning is small. The only effect is more small-scale structure. The decrease of SSH as a function of time is enhanced by 30%. This is due to the direct effect of heat release through the surface. For stable rings the impact of cooling is smaller; too small to recover the observed fast decay regime. The impact of convection on the baroclinic instability is weak. This is contrary to the case of convective chimneys. There, the stratification is already weak, and cooling can significantly change the initial stratification and reduce the Rossby radius. This may have a severe impact on the stability characteristics of the convective chimneys (*Legg and McWilliams*, 2000). In case of Agulhas rings, the stratification is much stronger and the depth penetration of the effect of cooling is much less. As a result the Rossby radius is hardly reduced by convection, and the dominant effect is the reduction of vertical shear in the upper layers. Subsequently, cooling slightly stabilizes the ring and the instability process develops marginally slower. Figure 5 shows the evolution of upper layer thickness for $\alpha = 1$ with cooling turned on at day zero. Comparing Figs. 5 and 2 we observe only small differences; the splitting process occurs somewhat later in the case when cooling has been turned on.

Discussion and Conclusions

Both adiabatic (β-)decay and baroclinic instability seem to account for the observed initial fast decay of Agulhas rings. The overturning associated with the β-induced movement implies cross-frontal mass exchange. Baroclinic instability mainly occurs for a wavenumber-2 disturbance which leads to ring splitting. The splitting itself hardly affects the SSH and density anomalies of the associated rings. Weaker, stable rings decay relatively more than twice as slow. Either the decay rate is a nonlinear function of the ring strength, or, baroclinic instability speeds up the overall decay. In that case, adiabatic decay does not explain the fast decay regime of the observed rings, as these seem more stable than the modeled rings. From the observed rings 30% split (*Schouten et al.*, 2000), while in the model a reduction in ring strength by a factor of 2 relative to observed still leads to a split.

The impact of cooling on the decay of Agulhas rings is rather modest. Both the strong stratification and relatively weak air/sea temperature contrasts seem to be responsible for this. Cooling on the eddy scale is strong; 115 W m^{-2} K^{-1} (*Drijfhout and Walsteijn* 1998). In a Gulf Stream-like environment, cooling of rings significantly affects the regional heat balance and the decay of warm-core Gulf Stream rings. In the case of Agul-

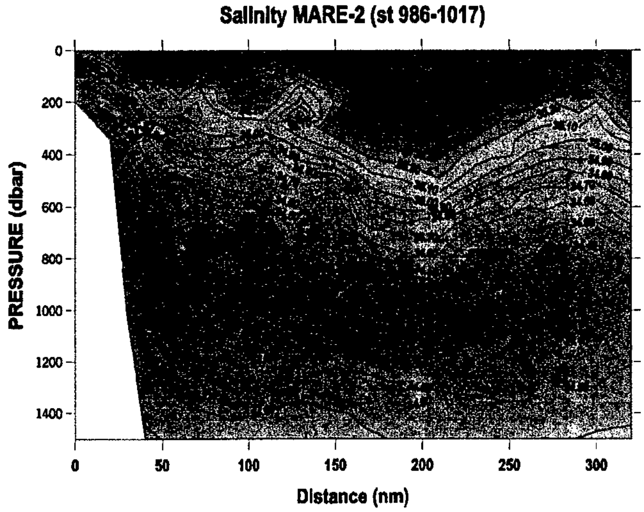

Figure 6. Zonal section of salinity through ring Astrid, taken at the second MARE cruise.

has rings, however, in general the depth penetration of cooling is too small to have such large impacts on the density and SSH anomaly of the rings. The decay rate is typically enhanced by 30%; for weaker rings the impact of cooling becomes less.

In our opinion, the most likely candidate to affect the decay of Agulhas rings we have overlooked so far, seems to be interleaving by double-diffusive driven thermohaline intrusions. Both in case of meddies and warm core Gulf Stream rings, double-diffusive driven interleaving has been identified as a main candidate in the decay of the mesoscale feature (e.g., *Tang et al.*, 1985, *Ruddick*, 1992). A zonal section through the edge of ring Astrid obtained form MARE-2 shows thermohaline intrusions to be operative between 100 and 150 nm from the coast and at 200 m depth (Fig. 6). A further analysis of the data is needed to identify whether these thermohaline intrusions have a double-diffusive origin. Also, the present numerical model has to be severely extended to be able to account for the development of double-diffusive-driven thermohaline intrusions. Such a study is left for the future.

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